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Friction Stir Scribe Joining of Al to Steel

PIYUSH UPADHYAY

Pacific Northwest National Laboratory

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June 7, 2017

Project ID #LM105

U.S. DEPARTMENT OF ENERGY

Project Overview

Project Timeline

- Start: Q4 FY2014
- Finish: FY2017
- 80% complete

Budget

- Total project funding
  - DOE – $1.2 M
  - Industrial cost share =$1.2M
- FY14 Funding - $400k
- FY15 Funding - $380k
- FY16 Funding - $420k

Technology Gaps/Barriers

- Joining and Assembly: High -volume, high -yield joining technologies for lightweight and dissimilar materials needs further improvement. (VT Multi-Year Program Plan 2.5.1F)
- Capacity to rapidly join Al sheet to steel in production like environment is not developed.

Partners

- **OEMs**
  - Honda R&D Americas Inc.
  - General Motors Company
  - Fiat Chrysler Automobiles
- **Supplier**

  Kuka Systems

Relevance and project objectives

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- Overall Objective:
  - Develop solid state joining technology needed to demonstrate fabrication of dissimilar Aluminum/steel assemblies to enable direct replacement of steel components with aluminum for high volume application. (addressing technology gap identified by VTO[1])
- Objective (FY 2016-FY2017)
  - Demonstrate targeted mechanical properties of the produced joints for harder steels and adhesive interlayers (> 70% static strength of weaker base metal / requirements set by individual OEM) .
  - Complete and validate structure-property predictive model
  - Transfer FSS process to OEMs and supplier.

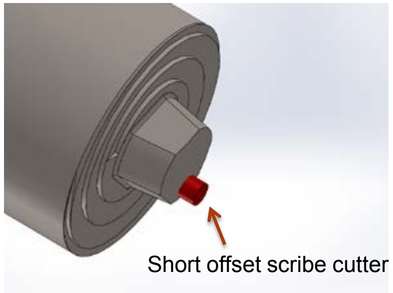
[1]Light-Duty Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials, Workshop, pp12, 2013, US DOE VTO

Project Milestones

Month/Year	Milestone or Go/No-Go Decision
June 2016 **Milestone**	**Initiate predictive modeling of FSS joint** **Complete**
September 2016 **Decision Gate**	**Integration of FSS with stationary shoulder tool** **Complete**
March 2017 **Milestone**	**Demonstrate Friction Stir Scribe process at OEM/ suppliers facility** • Delayed due to time required to acquire tooling and materials at industrial partners. **September 2017**

Technical Approach

- The project utilizes a unique solid state joining method capable of bonding drastically different melting point materials, Friction Stir Scribe technique to produce joints between automotive aluminum and steel sheets.



- **Task 1: Baseline weld development and characterization**
  - Task 1.1. Materials and Configurations
    - Determine specific material combinations and configuration of interest to each OEM
  - Task 1.2. Weld development
  - Task 1.3. Baseline Characterization
    - **Decision Gate:**
      - **Strength target of 70% of weaker base material**
      - **Strength target set by individual OEM**

Technical Approach

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- Task 2: Extended weld development & material selections
  - Task 2.1 Material variations
  - Task 2.2 Scribe tool optimization
  - Task 2.3 Retractable tool technology
  - Task 2.4 Stationary shoulder application
    - Decision Gate:
      - Stationary shoulder integration with scribe technology
- Task 3: Prototype development and demonstration
  - Task 3.1. Prototype design
  - Task 3.2. Prototypical demonstration
    - Collaborators to setup prototypical demonstration for joining Al/Steel using FSS in coordination with PNNL.
- Task 4: Computational tool development and validation
  - Task 4.1. Predicative development
  - Task 4.2. Model Validation

Technical Approach:

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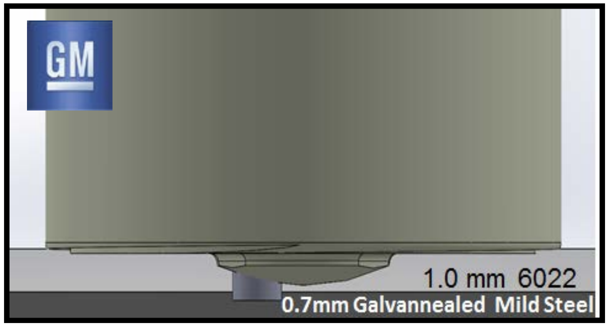
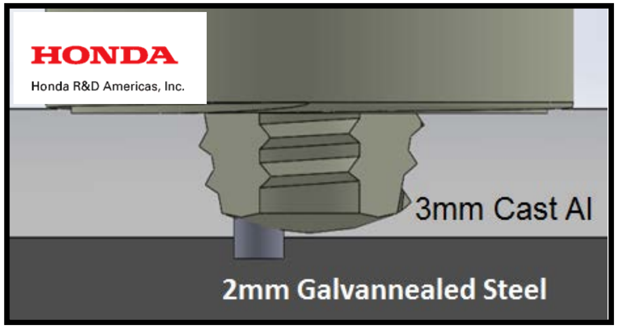
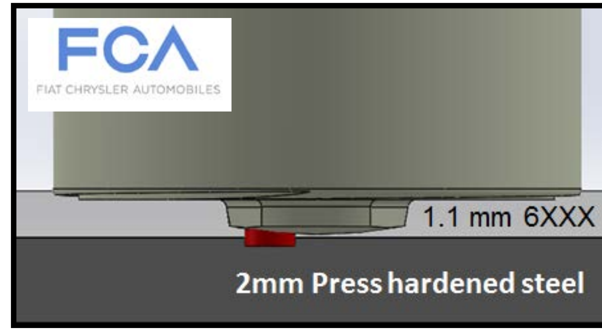
Material Set Overview by OEMs with intended application







AA 6022 ↔ **GA Mild Steel** (GMW2GA)

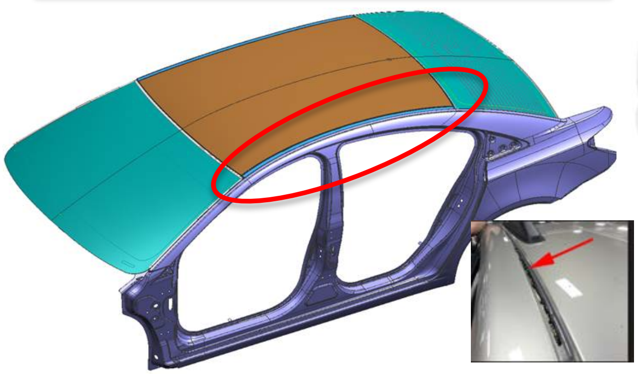
Cast Al ↔ **GA Steel** (JAC 270); **590, 780, 980, 1180 MPa Steels**

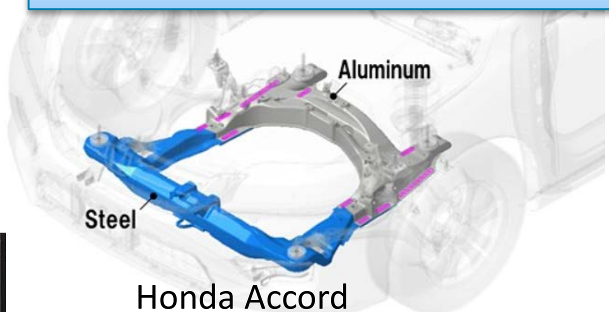
6xxx (Surfalex 6s) ↔ **UHSS** (USIBOR); **TRIP 590**

Roof Ditch steel to Aluminum outer

Front Sub-frame Engine Chassis assembly

A Pillar/ B Pillar, Adhesives





Surface finish, thin sheet

Non uniform thickness in Cast Al

Stronger steel

Project Schedule and Progress

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	FY 14	FY2015				FY2016				FY2017		
Quarter	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**
Task 1: Baseline weld development and characterization												
1.1. Material & configurations												
1.2. Weld development												
1.3. Baseline characterization												
Decision Gate: Joint performance												
Task 2: Extended Weld Development & Material Selections												
2.1 Material variations												
2.2. Scribe tool optimization												
2.3. Retractable tool technology												
2.4 Stationary shoulder application												
Decision Gate: applicability of extended technologies												
Task 3: Prototype Development and Demonstrations												
3.1. Prototype design												
3.2. Prototypical demonstrations												
Task 4: Computational Tool Development and Validation												
4.1. Predictive tool development												
4.2. Model validation												

FY16 Go/No-Go

FY17 Milestone

FY16 Milestone

Technical accomplishments: Task 2.4

Integration of Stationary shoulder (FY 16 Decision gate)

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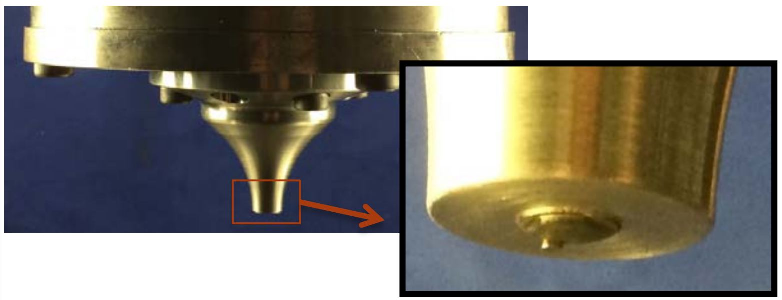
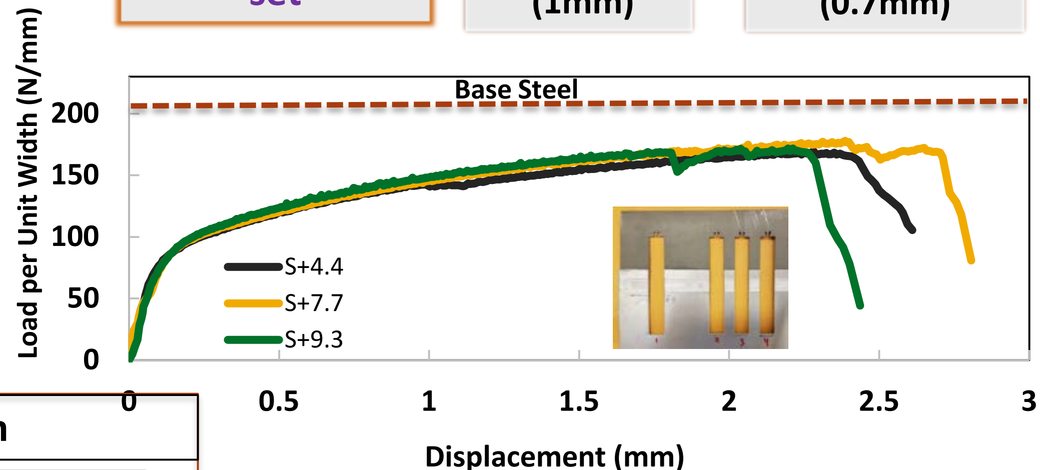
Stationary shoulder with FSS setup

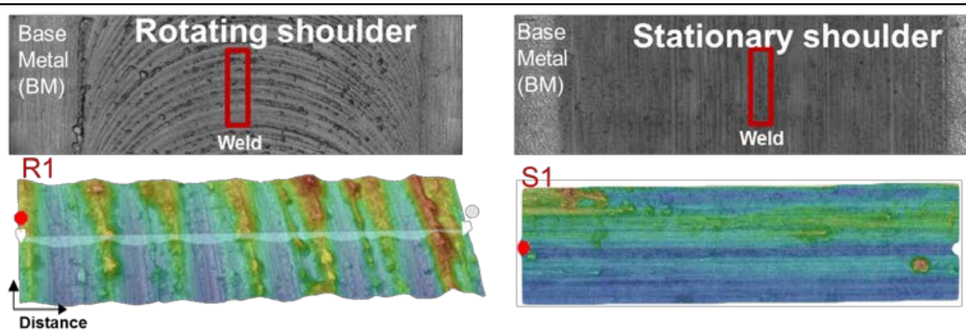


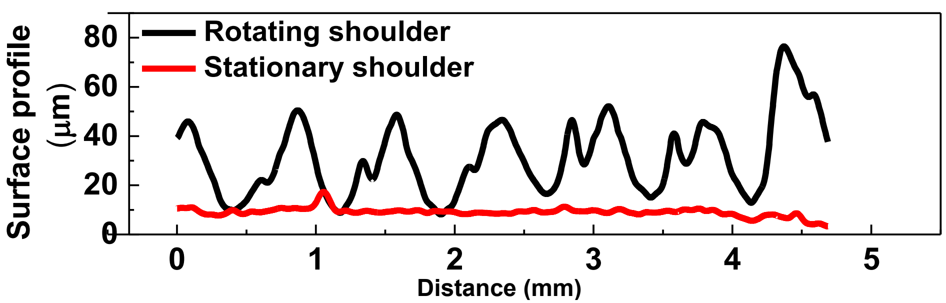
GM material set

AA 6022 (1mm) ↔ **GA Mild Steel (0.7mm)**



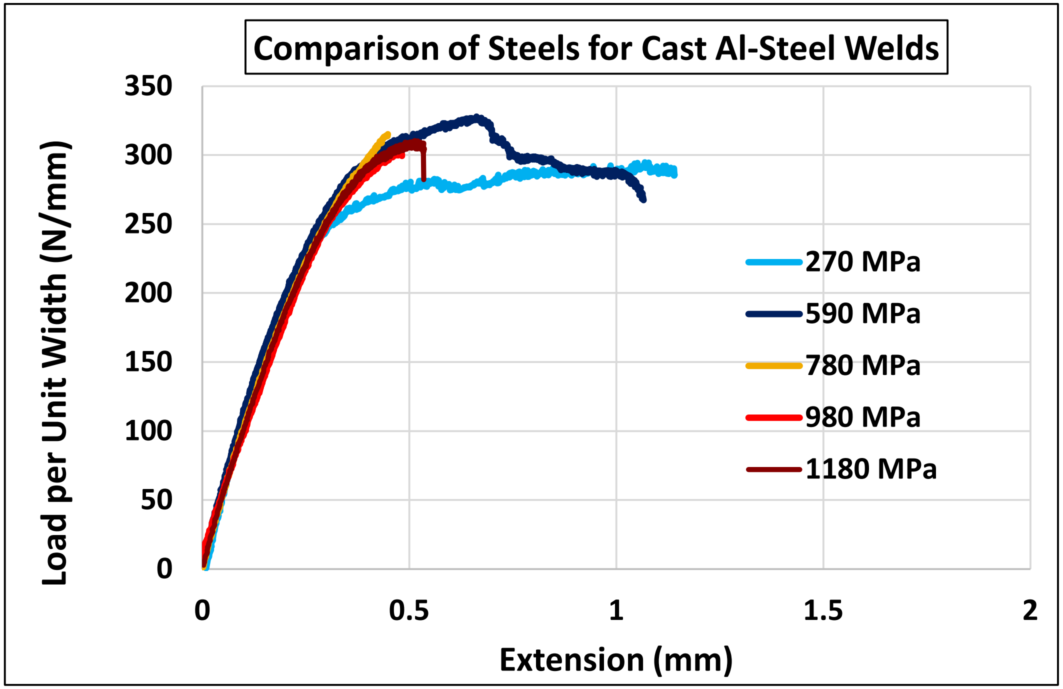
Weld surface roughness comparison





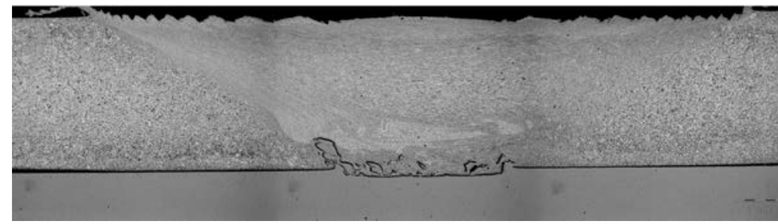
- Load carrying capacity 85% of the base steel was demonstrated with Stationary shoulder integrated Friction stir scribe joining.
- Weld crown with stationary shoulder is demonstrated to be higher surface finish compared to conventional rotating shoulder.

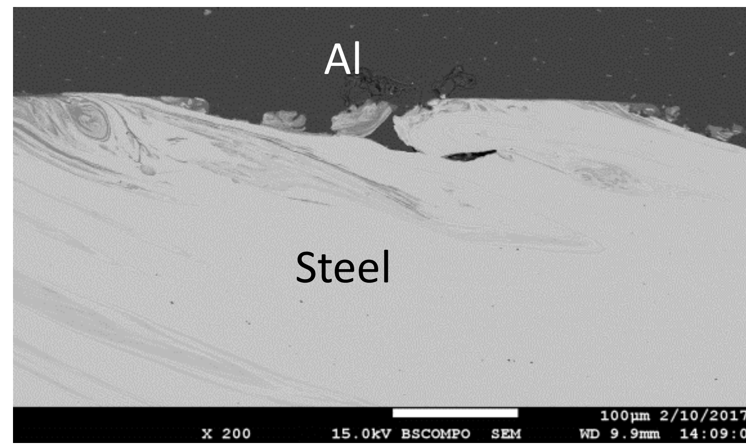
Technical accomplishments: Task 2.1, 2.2
Joining Aluminum- progressively harder steels



Honda material set

3mm Cast Al ↔ GA Steel 270, 590, 780, 980, 1180





- Demonstrated joining of progressively harder coated steels (270, 590, 780 and 980 MPa) to Cast Aluminum coupons exceeding OEM lap shear test requirement.
- Scribe tool is likely breaking intermetallic layer and dispersing IMCs in the interface region.
- Nature of IMCs varied depending on protective coatings on different steel sheets.

Technical accomplishments: Task 2.1, (cont.)
Wrought Aluminum- Hard Steels, Adhesive interlayers

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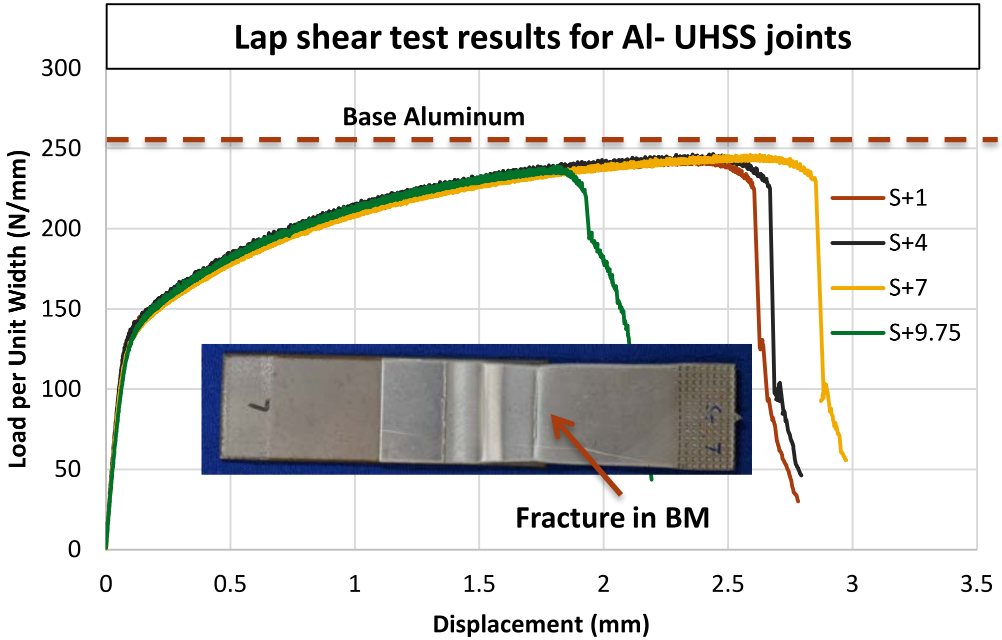
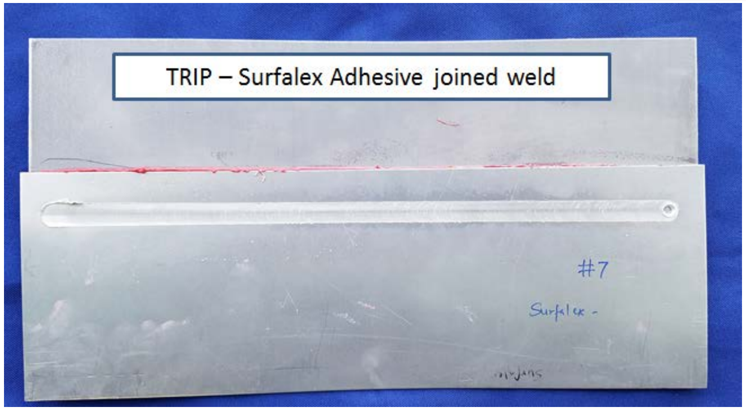


FCA material set

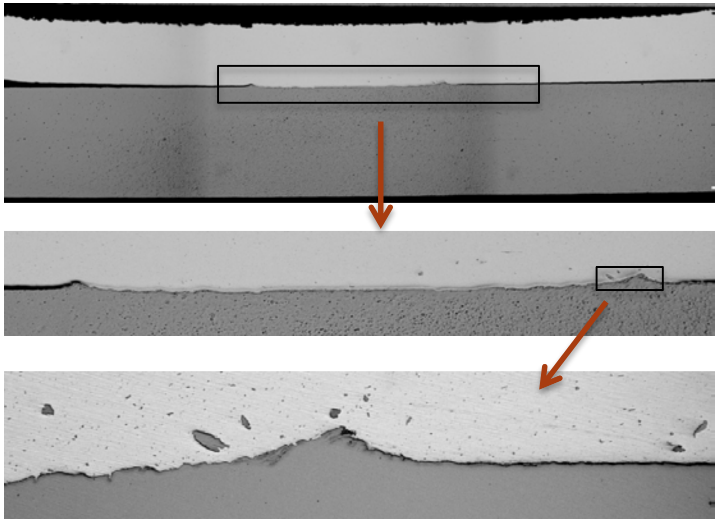
6xxx (Surfalex 6s, 1mm)

UHSS (USIBOR, 1500 MPa)

TRIP 590



Joint cross-section with adhesive interlayer



Al- UHSS joint cross-section

- Demonstrated viable joining of TRIP 590 to Aluminum
- Demonstrated viable joining of TRIP 590 – Al with adhesive interlayer. (After paint bake cycle ~90% strength compared to adhesive only joints has been demonstrated)

Technical Progress: Demonstrate technology outside the lab. (Task 3)

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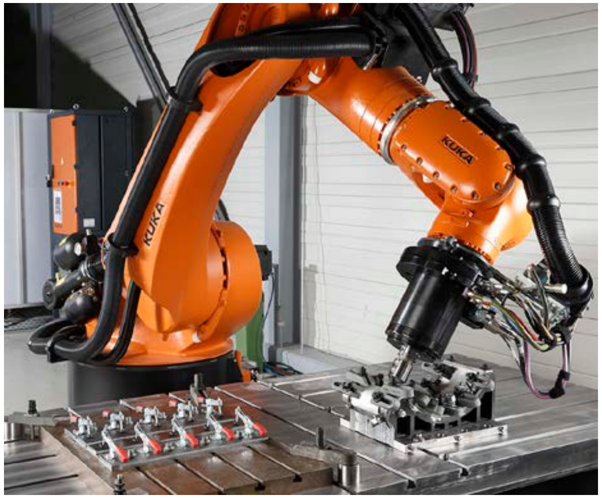
Retractable scribe tools for GM FSW machine

Gantry machine at GM facility



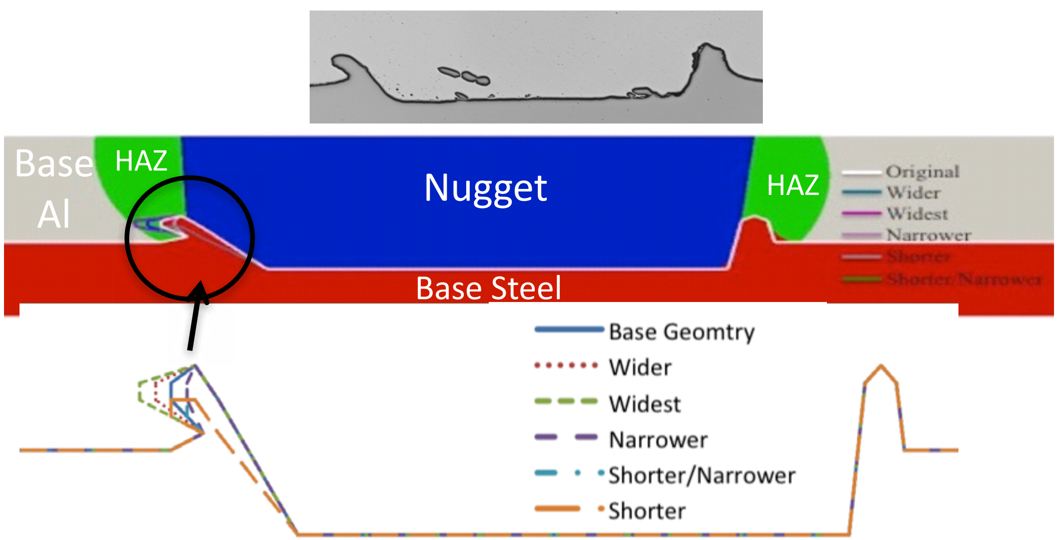
KUKA Robot

- Having demonstrated viability of FSS joining at PNNL we are moving forward to demonstration at KUKA and GM facility.
- First round of retractable FSS tools have been produced and are ready for implementation at GM facility.
- Tools needed for KUKA robot demonstration are in production in preparation of demonstration.
- Corrosion testing is currently being planned and/or performed by each OEMs.

Structure-Property Modeling: Setup

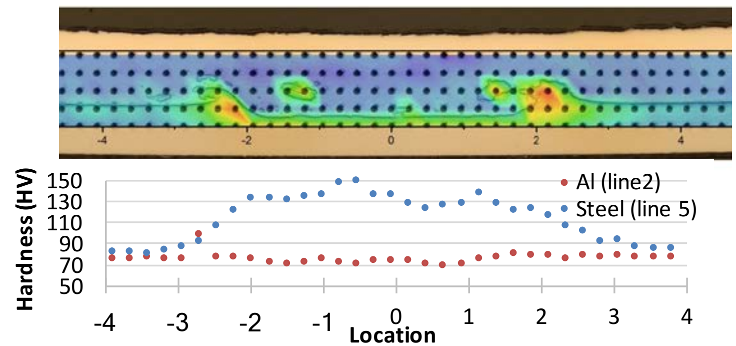
- Base hook morphology was generated from a representative weld. Modified versions of the hook features were then created in the model to account for hook variations along weld length.
- Material regions were defined to capture property changes due to welding (Micro-hardness data).
- To account for hook asymmetry, joint was loaded from both advancing and retreating sides.

Model Setup

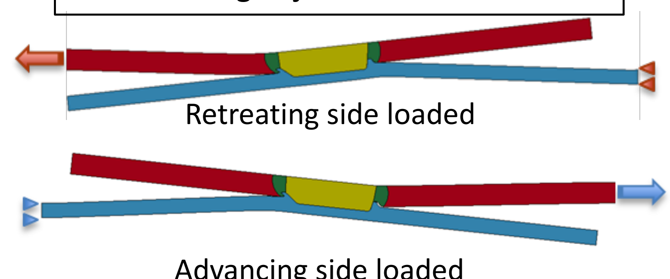


Modified hook features input in model

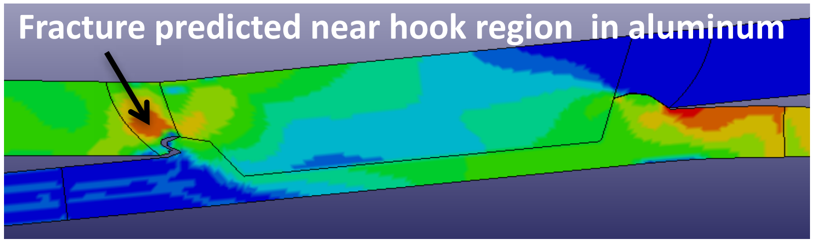
Microhardness dataset (input in model)

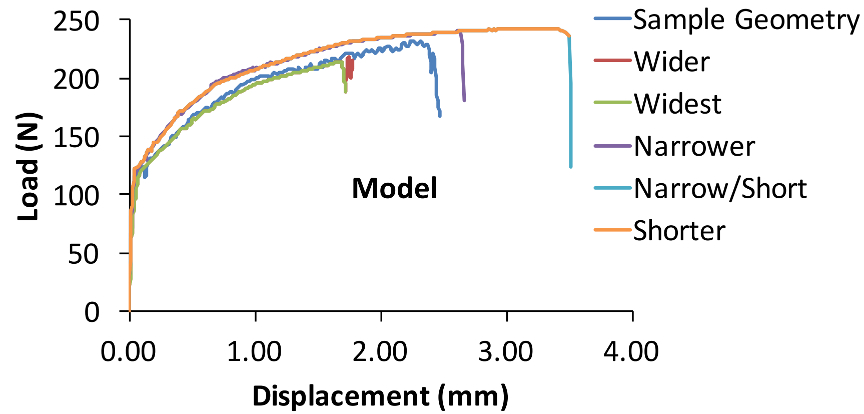


Loading of joint in the model

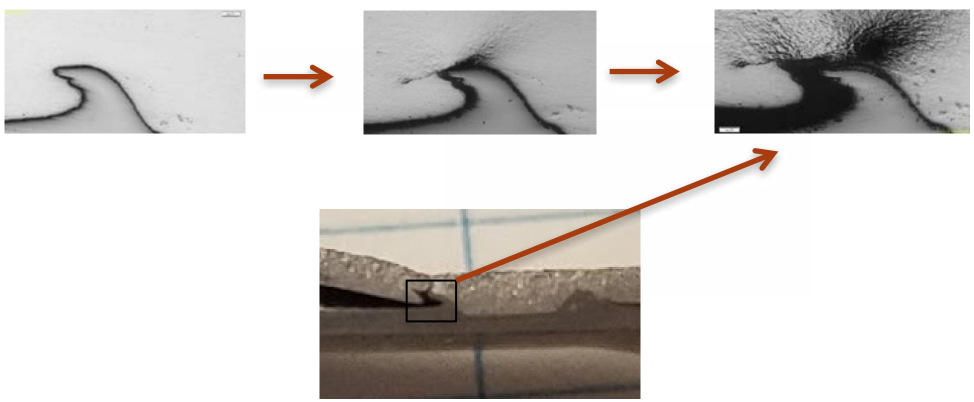


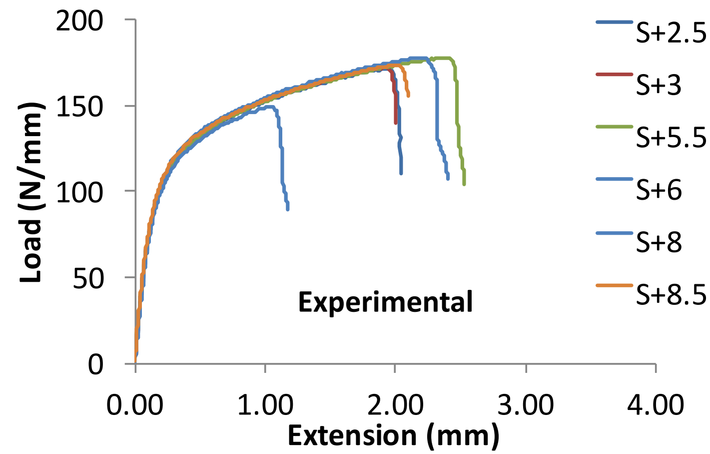
Structure-Property Modeling: Results





Interrupted test showing fracture propagation





- The model has been able to accurately predict the fracture location and mode.
- Hook morphology showed some impact on extension and strength of lap joints.

Response to Reviewer Comments

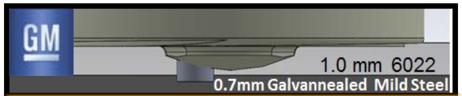
- Reviewer: *"observed a very nice mix of different Al to steel combinations, and noted good directional results showing the potential for the process.. Suggested adding some microstructural characterization to the study.*
  - **Response**: Microstructural characterizations including micro-hardness, grain structure and nature of intermetallic compounds between several Aluminum and steel joints have been performed. Some of the characterization results are included in this presentation.
- Reviewer: *observed an excellent work plan and objectives for subsequent years of funding.. would welcome specific info on tool wear/life as a function of linear friction stir scribe length.*
  - **Response**: As the objective of the project was to show viability of the process in joining wide variety of Aluminum and steels, we did not perform systematic study on tool wear/life. We have demonstrated that H13 (FSW tool) + WC-Co (scribe) functions well up to ~1180 MPa steel. Joints with ultra high strength steels can be made with alternative tool materials. Tool life issues with harder steels like built edge formation are presented in technical backup slide and issues/assumption slide.
- Reviewer " inquired if there is a need to evaluate corrosion performance, and whether it is possible to incorporate adhesive joining with the proposed process.
  - **Response**: Participating OEMs are currently conducting corrosion study on joints. This FY we demonstrated FSS joining with adhesive interlayer. (results shown in this presentation)

Collaboration and coordination

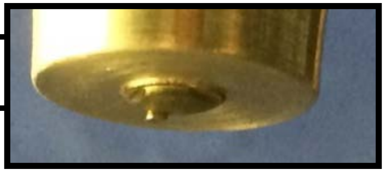
- Private Collaborations (OEMs and Supplier)
  - General Motors
    - Providing relevant aluminum and steel sheets
    - Providing guidelines and requirements for Stationary shoulder tool design.
    - Supply of prototype demonstration components (Roof ditch, RSW steel)
    - Conducting corrosion and peel testing of FSS joints.
  - Honda
    - Providing relevant Aluminum and steel sheets
    - Conducting corrosion testing of FSS joints.
    - Supply of prototype demonstration components (Castings)
  - FCA
    - Providing relevant Aluminum and steel sheets
    - Providing required adhesives and bake cycle for the joints
    - Conducting corrosion testing of FSS joints.
  - KUKA
    - Providing facility and equipment for demonstration of FSS joining
    - Integration of Stationary shoulder with FSS in robotic application.

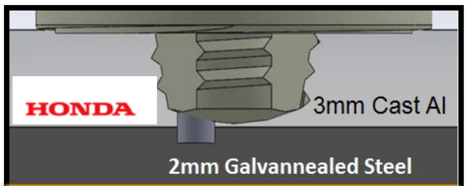
Remaining Challenges and Barriers

- The primary remaining challenge is to transfer the FSS technique from lab to industry. Following barriers have been identified for each OEM material set.

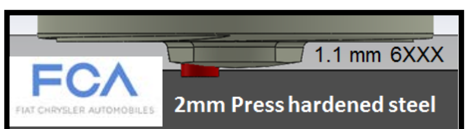


Roof ditch application requires superior surface finish → Stationary shoulder tooling; Weld parameters, Tool geometry.



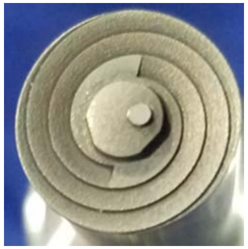


FSS process needs to accommodate non uniform thickness in Cast Al → Weld parameters, Tool geometry.



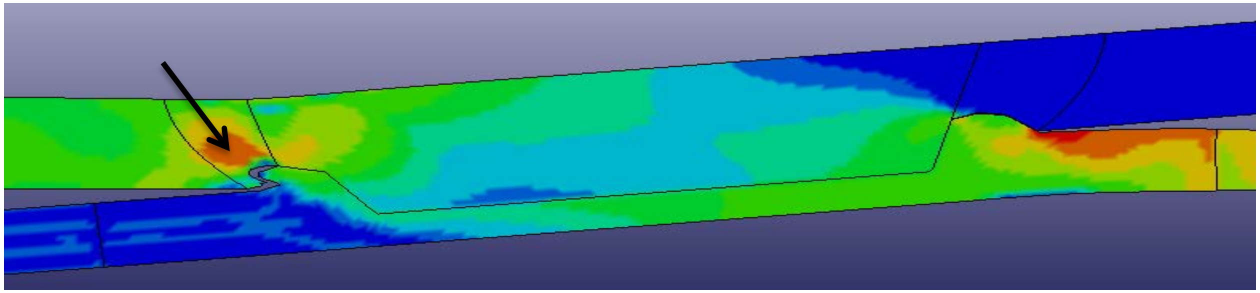
FSS process needs to accommodate adhesive interlayer → Weld parameters, Tool geometry.

FSS tooling needs to demonstrate joining with UHSS steel while maintaining acceptable tool life. → Weld parameters, Tool geometry; Alternative tool materials



Planned Future Work

- 2017: We will focus on prototypical demonstrations of the FSS joining process by industry partners utilizing the process knowledge gained over the course of this project.
- We will complete predictive model validation that will broaden understating of interface geometry effects on joint properties.



Any proposed future work is subject to change based on funding levels.

Project Summary

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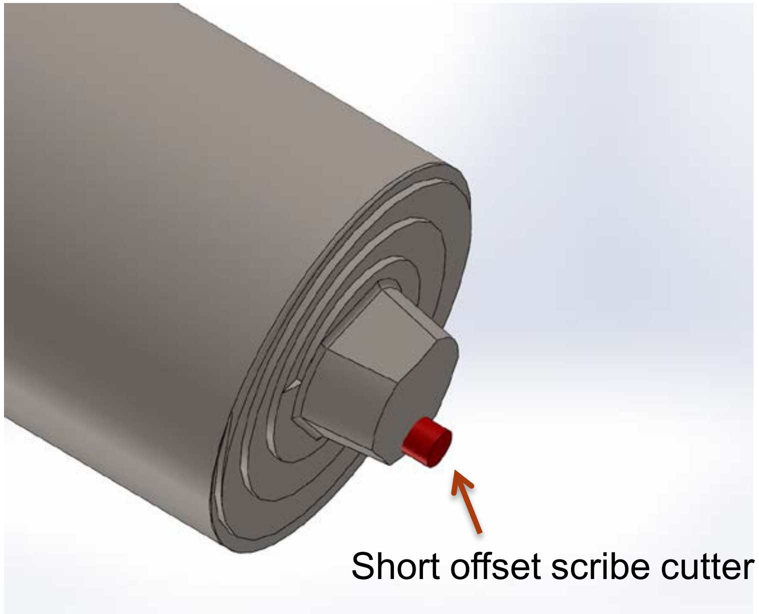
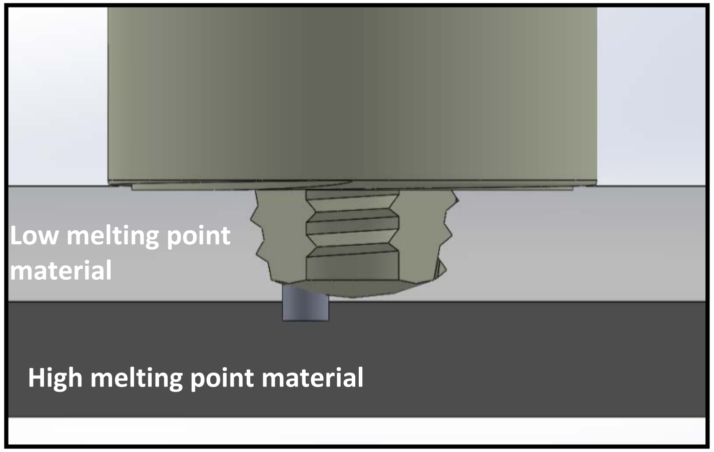
- This project has been able to demonstrate feasibility of Friction stir scribe joining in several combinations of automotive aluminum to steel sheets as selected by 3 OEM partners.
- In FY16 we demonstrated integration of stationary shoulder design with FSS process to produce viable Aluminum - steel joints.
- FY 16: We demonstrated viable joints in several additional progressively harder steels (270 MPa to 1180 MPa steel) and with adhesive interlayer.
- FY 16:Structure- property modeling developed in the project has resulted in the ability to predict fracture location and joint strength.
- In collaboration with partners we are getting ready to demonstrate this joining technique in an OEM (Gantry machine) and a supplier's facility (robot).

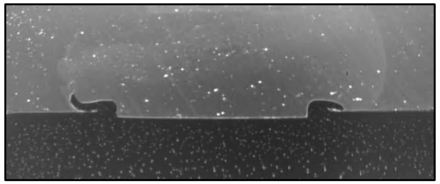
Technical Back-Up Slides

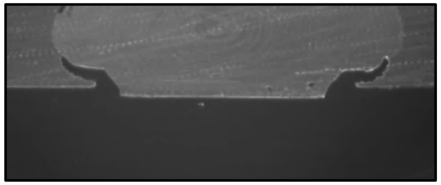
Friction Stir Scribe (FSS): The basics





Simultaneous FSW and cutting

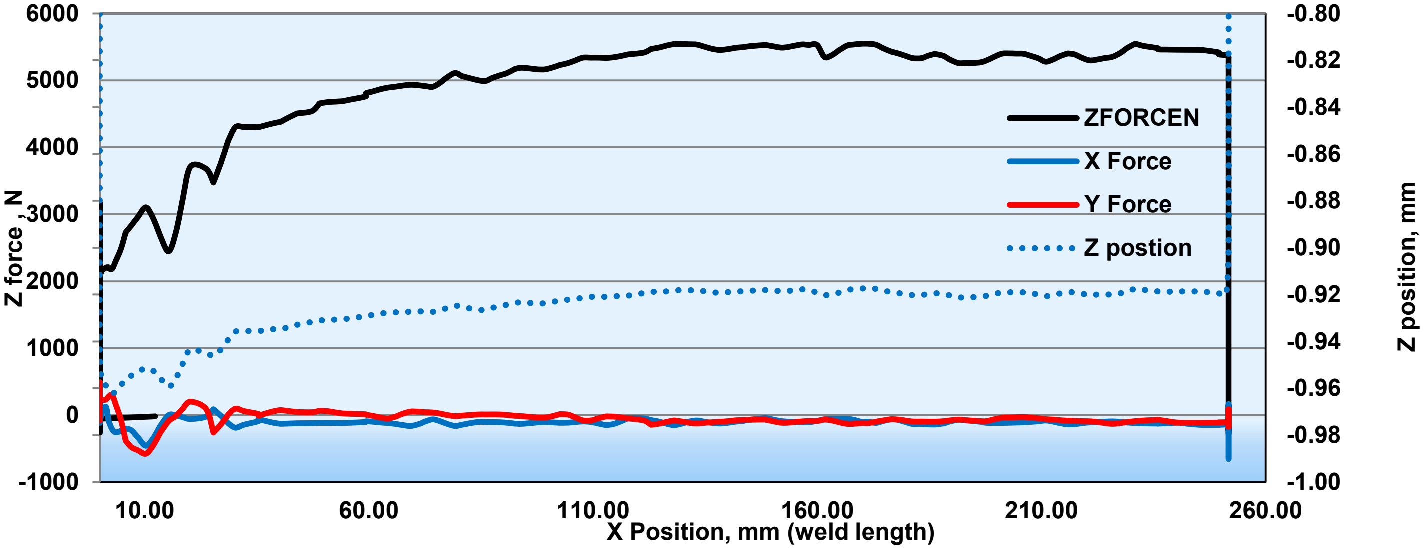




Friction stir scribe tools, Scribe: W-C

Forms an in-situ mechanical and metallurgical joint because of insitu machining of harder material.

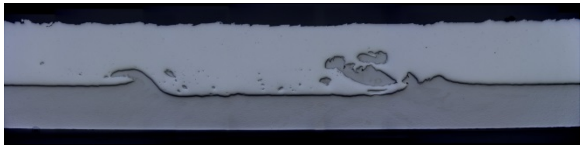
Force and position data acquired during welding



Weld#2015-01-15#4- Plunge depth: 0.99mm @ 1950RPM, 750m/min, Scribe length: 0.42mm

Near Plunge (45mm from plunge)

Middle (125mm from plunge)

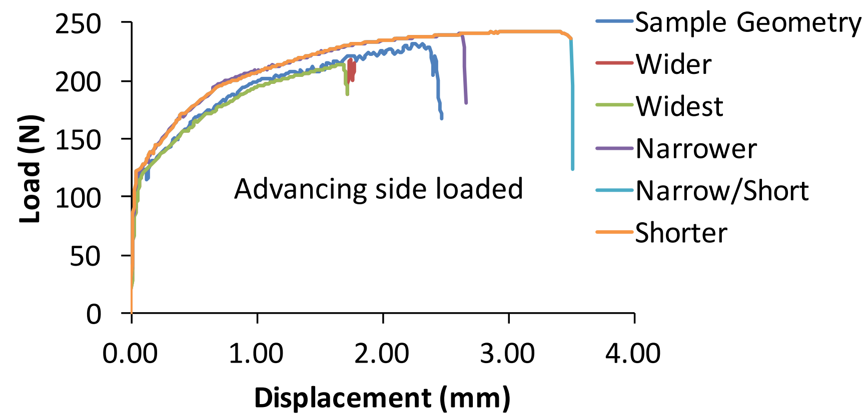


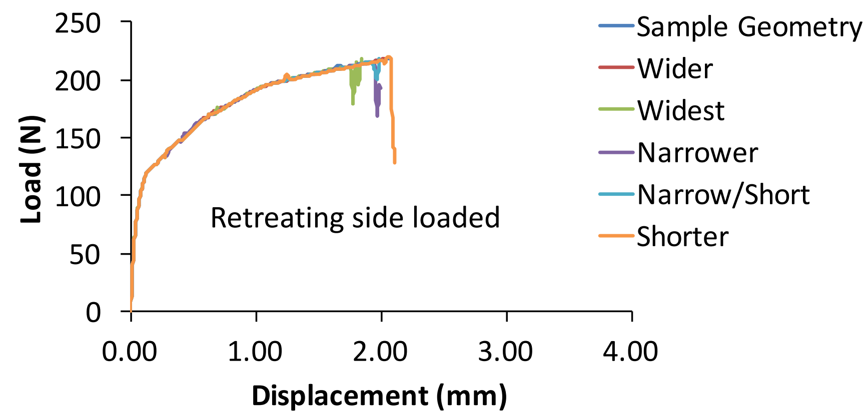
Near End (225mm from start)

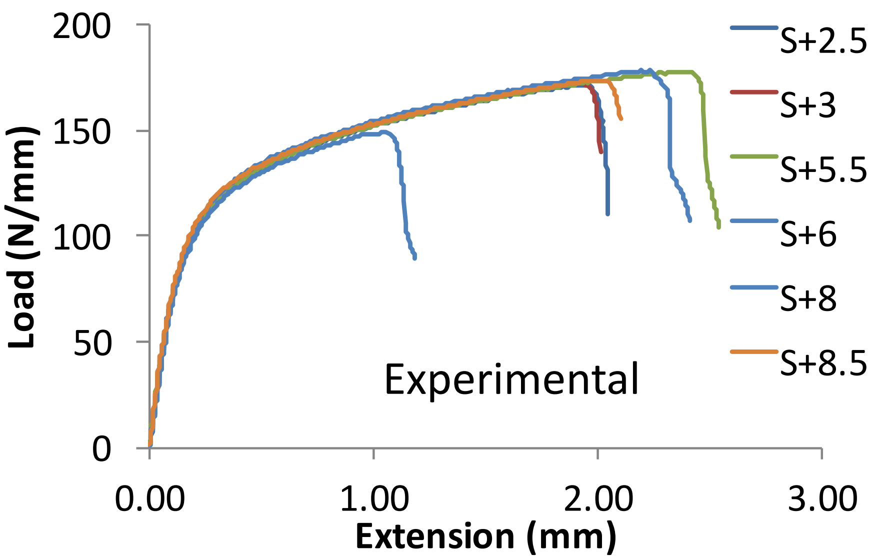
Force signature and z position after initial startup is relatively stable. Data such as this is critical in design of robotic FSW systems.

2D Simulation Results

- All results are for 2D plane ε modeling.
- The retreating side hook was not modified; therefore loading from this side shows minimal impact from advancing hook morphology.
- Loading the advancing side hook (which was modified) shows more variation. It also shows higher strength.
- Example experimental results are shown for comparison







Base Metal Characterization

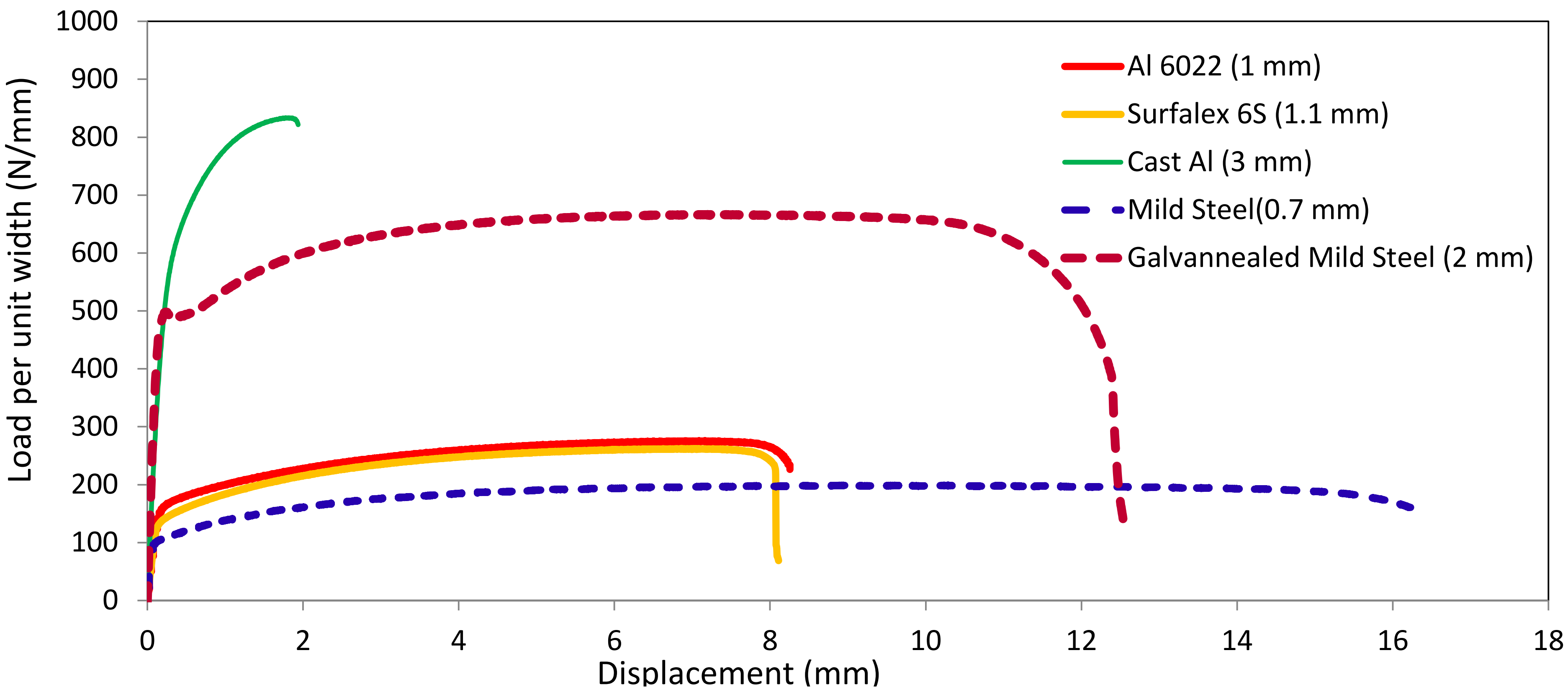
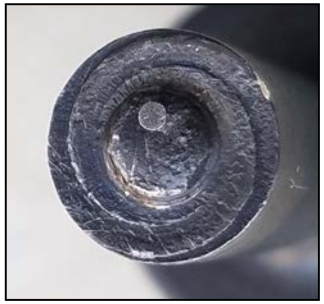


Chart shows a range of material properties of Aluminum and Steels being investigated in the project. Standard ASTM-E8 test results are represented in terms of load per unit width for ease of comparison). Note that thickness of different materials vary and hence this chart is not appropriate reflection of intrinsic mechanical property of corresponding material.

UHSS tooling challenge and potential solutions

As welded FSS tool



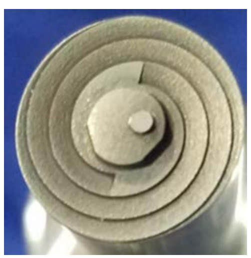
After caustic cleaning

USIBOR-After Cleaning

With USIBOR (1500 MPa) built up edge around the scribe changes the cutting edge significantly thus affecting repeatability.

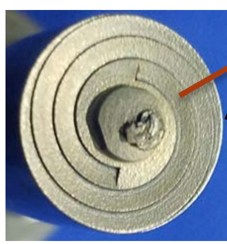
- **Challenge:** For UHSS case a tool can only produce 2-3 welds (11” long possible) without tool change.
- **Potential Solution:** Uni-body tool with both scribe and tool made out of hard material (W-C-Co and PCBN)

W-C-Co Uni-body tool results

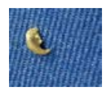


As received

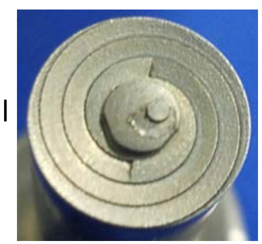
Welding



Cleaned tool after 36” long weld



After Steel removal



W-C-Co uni-body tool resulted in lesser extent of bonding to steel suggesting lower susceptibility to built-up edge formation. Steel was easily dislodged from the tool tip.